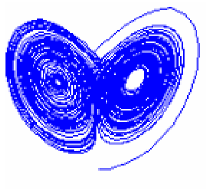
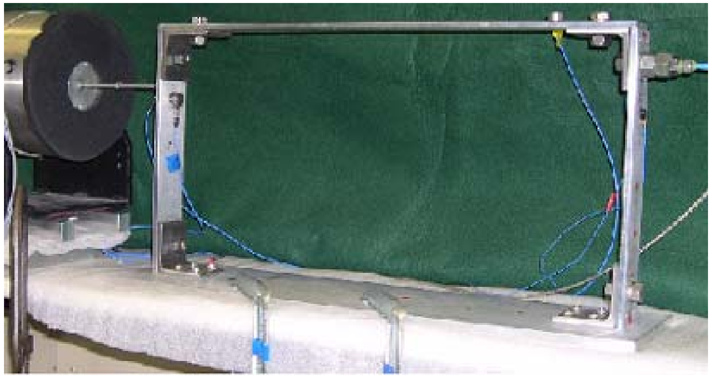
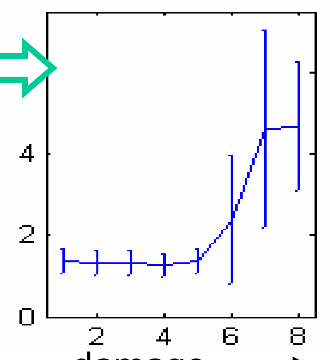
Structural Damage Detection Using Chaotic Interrogation







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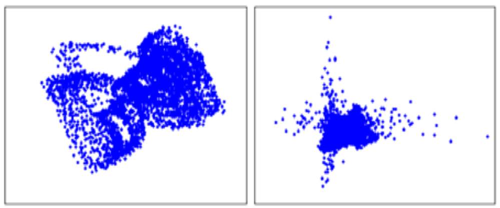
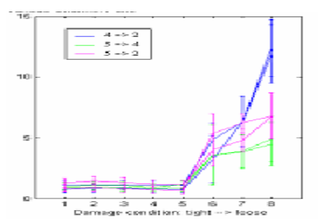
Overview

Structural health monitoring



Chaotic interrogation method

Experimental procedure



Damage detection results

Structural health monitoring

- Assess integrity of structural systems
- Reduce maintenance costs
- Extend operational lifetime
- Goals:
  - Identify damage
  - Estimate extent
  - Locate damage
  - Predict future life of structure

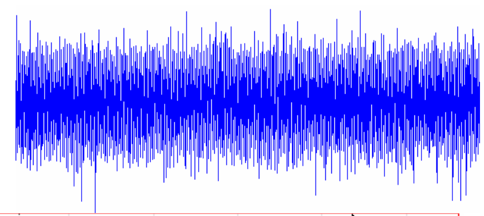
Degradation of bolted joints

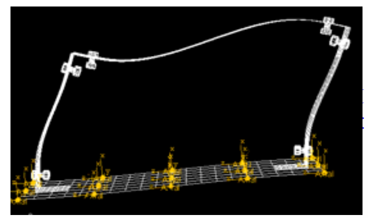
- Bolts extensively used in large systems
  - Popular for resisting moments
  - Ease of disassembly

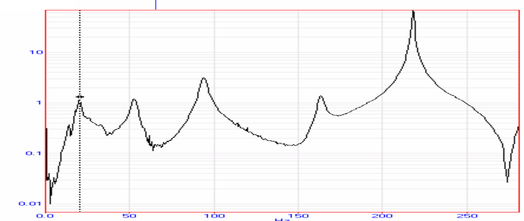
- Degradation
  - Loosen under creep, vibration, shock, thermal loading
  - Failure often catastrophic

Damage detection strategies

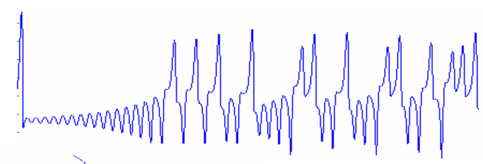
- Traditional modal-based approaches
  - Stochastic, broad-band excitation
  - Analyze transient dynamic behavior

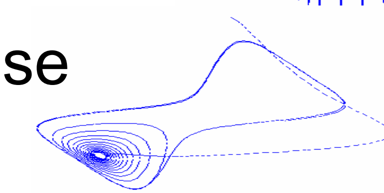




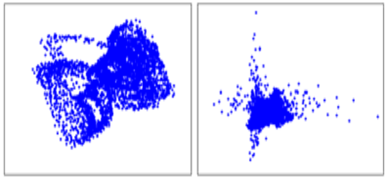


- New method: chaotic interrogation
  - Deterministic input
  - Analyze steady state response

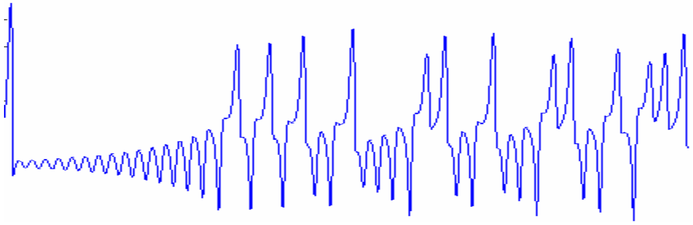




Chaotic interrogation method



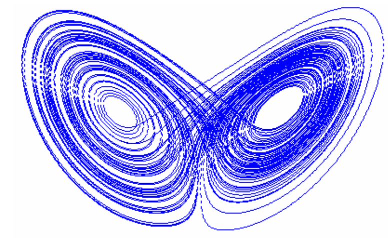
- Determinism of chaotic input
  - Repeatable excitation for probing structure
  - Generated by deterministic ordinary differential equations



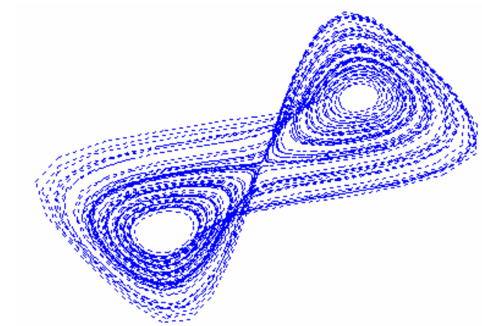
- Controllable dimensionality of steady state response
  - High enough to reflect dynamic range of structure
  - Low enough for robust calculation of diagnostic feature

Time series analysis concepts

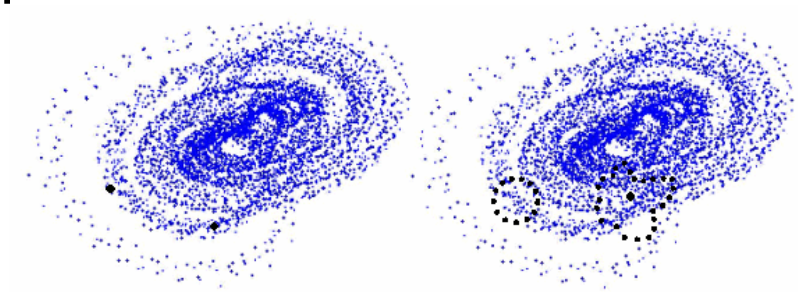
- Visualizing attractors in phase space



- Reconstructing attractors in practice



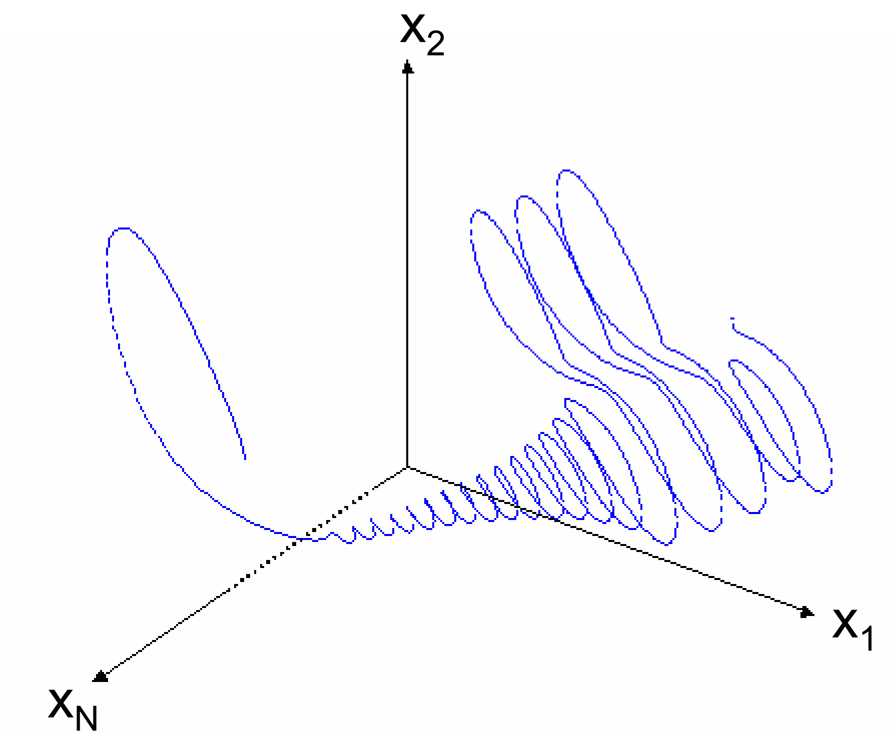
- Comparing attractors with prediction error



Visualizing systems in phase space

- System of 1st order differential equations

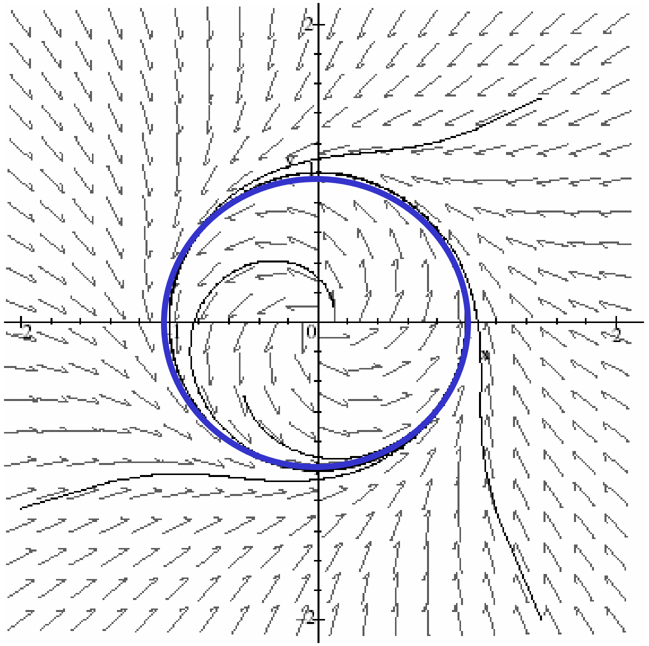
$$\dot{x}_1 = F_1(\vec{x}, \dot{\vec{x}})$$
$$\dot{x}_2 = F_2(\vec{x}, \dot{\vec{x}})$$
$$\vdots$$
$$\dot{x}_N = F_N(\vec{x}, \dot{\vec{x}})$$



- Plot in *N*-dimensional space

System evolution into attractors

- Dissipative & stable systems eventually collapse onto lower dimensional orbit
  - One-dimensional limit cycle:

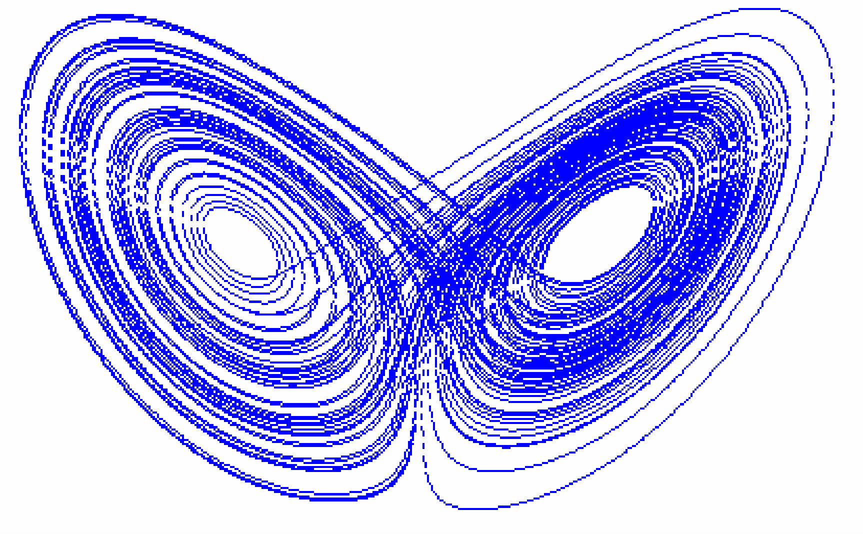


- Steady-state response: ‘attractor’

Chaotic attractors

- Sensitive to small changes in parameters
- Lorenz attractor:
  - Inspired by weather modeling research
  - 3-dimensional system

$$\dot{x} = q(y - x)$$
$$\dot{y} = -xz + rx - y$$
$$\dot{z} = xy - bz$$



Reconstruction of attractors

- Difficult to measure all degrees of freedom in real systems
- System dynamics captured qualitatively in one degree of freedom

$$
\begin{array}{c}
\dot{x}_1 = F_1(\vec{x}, \dot{\vec{x}}) \\
\dot{x}_2 = F_2(\vec{x}, \dot{\vec{x}}) \\
\vdots \\
\dot{x}_N = F_N(\vec{x}, \dot{\vec{x}})
\end{array}
\quad \Rightarrow \quad
\left\{
\begin{array}{c}
x_1(t) \\
\dot{x}_1(t) \\
\vdots \\
x_1^{(N)}(t)
\end{array}
\right.
$$

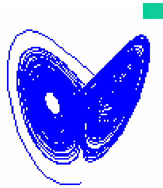
Delay coordinate reconstruction

- Time-shifted delay of original time series rather than continuous derivatives

- Embed x with
  T time step delays
  for m dimensions

$$\begin{matrix} x_1(t) \\ \dot{x}_1(t) \\ \vdots \\ x_1^{(N)}(t) \end{matrix} \quad \Rightarrow \quad \begin{matrix} x_1(t) \\ x_1(t+T) \\ \vdots \\ x_1(t+(m-1)T) \end{matrix}$$

- Captures equivalent topology (Takens, 1981)
- Useful for discrete data acquisition

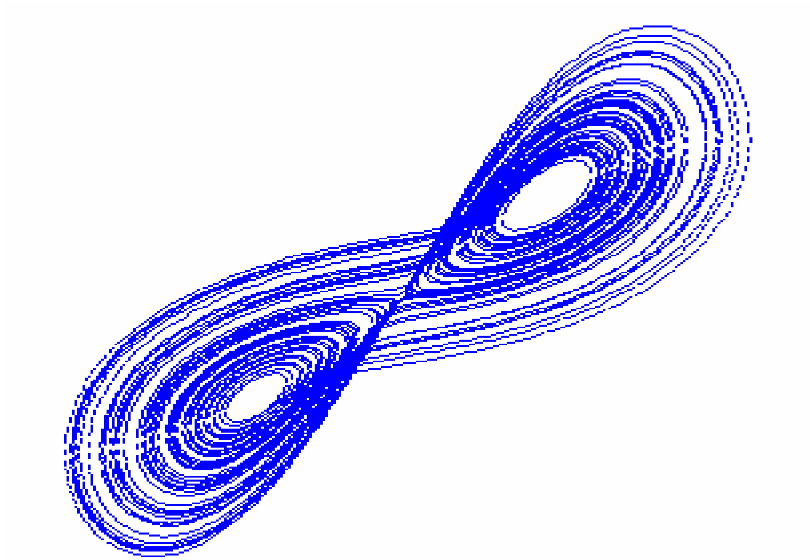


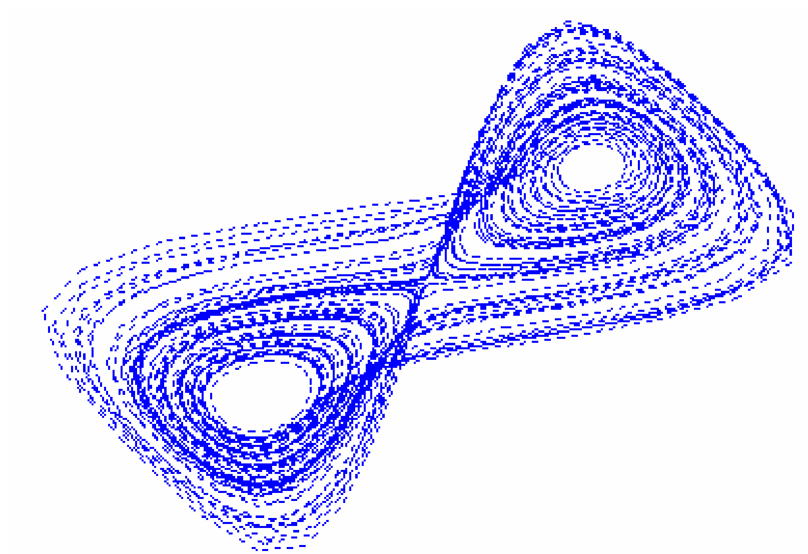
Reconstruction of Lorenz attractor

$$\dot{x} = q(y - x)$$
$$\dot{y} = -xz + rx - y$$
$$\dot{z} = xy - bz$$

$$\Rightarrow$$

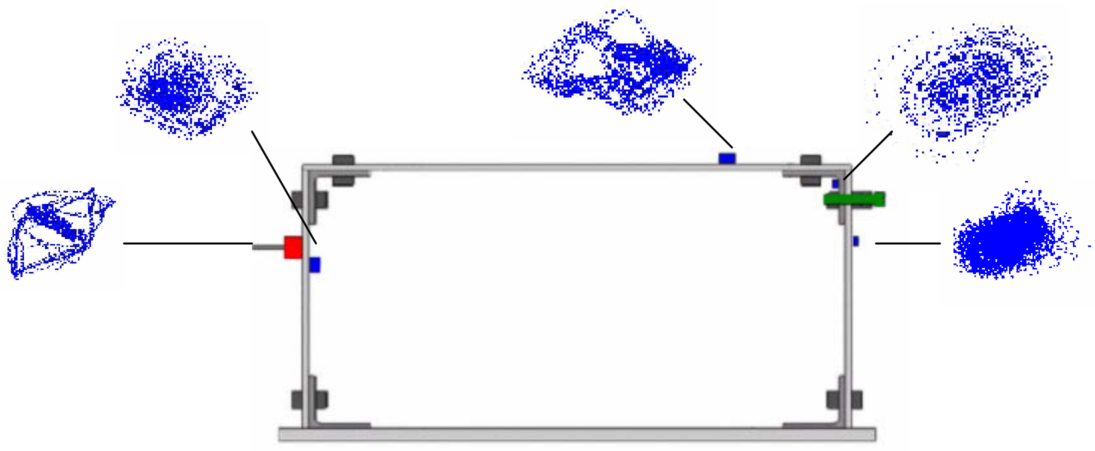
$$x(t)$$
$$x(t+T)$$
$$x(t+2T)$$



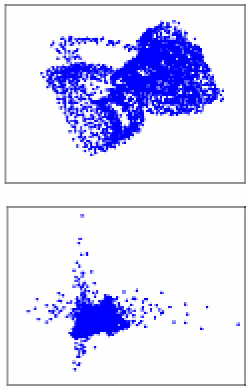


Comparing attractors

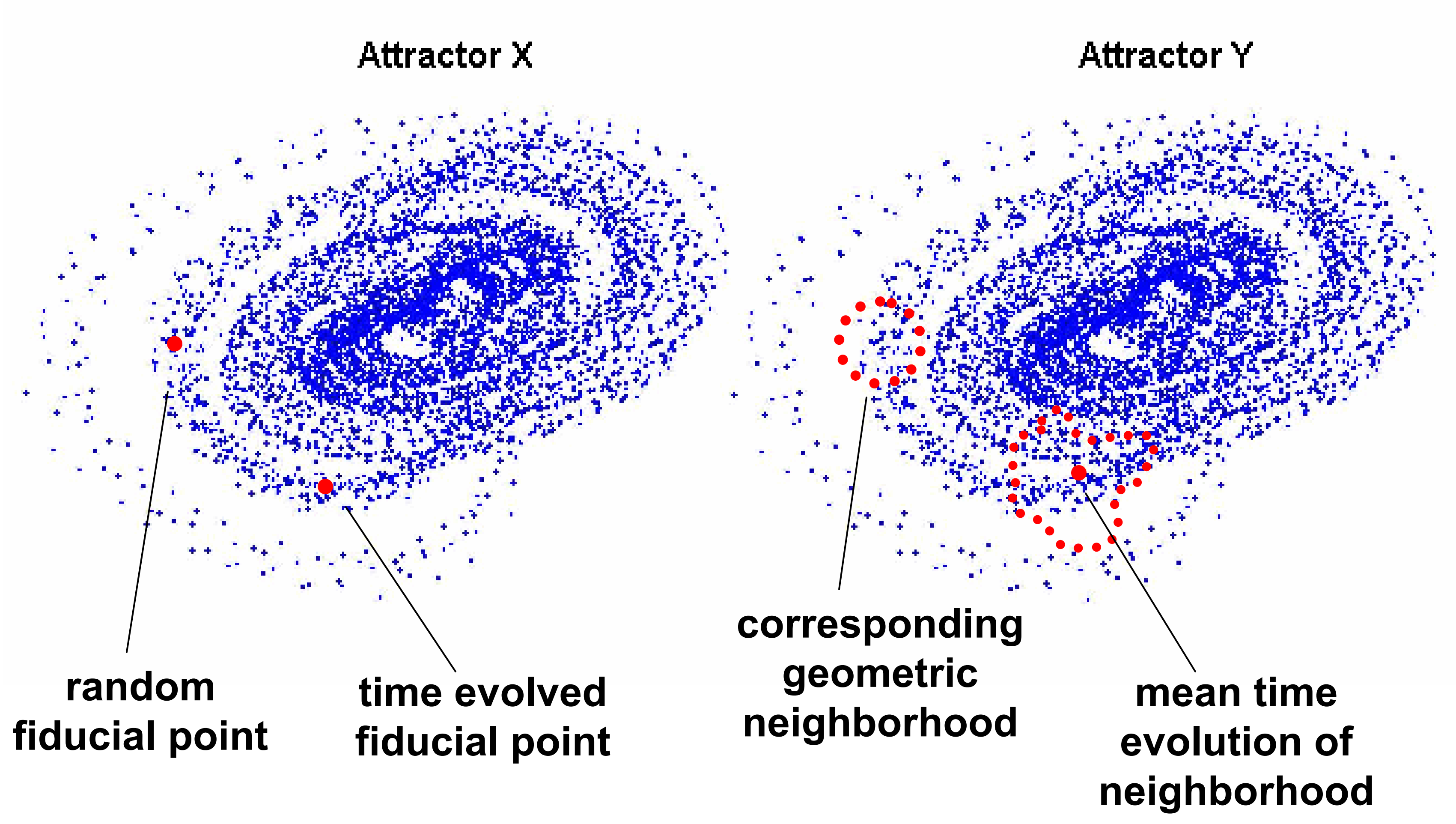
- Measure responses from different locations
- Reconstruct attractors from data signals



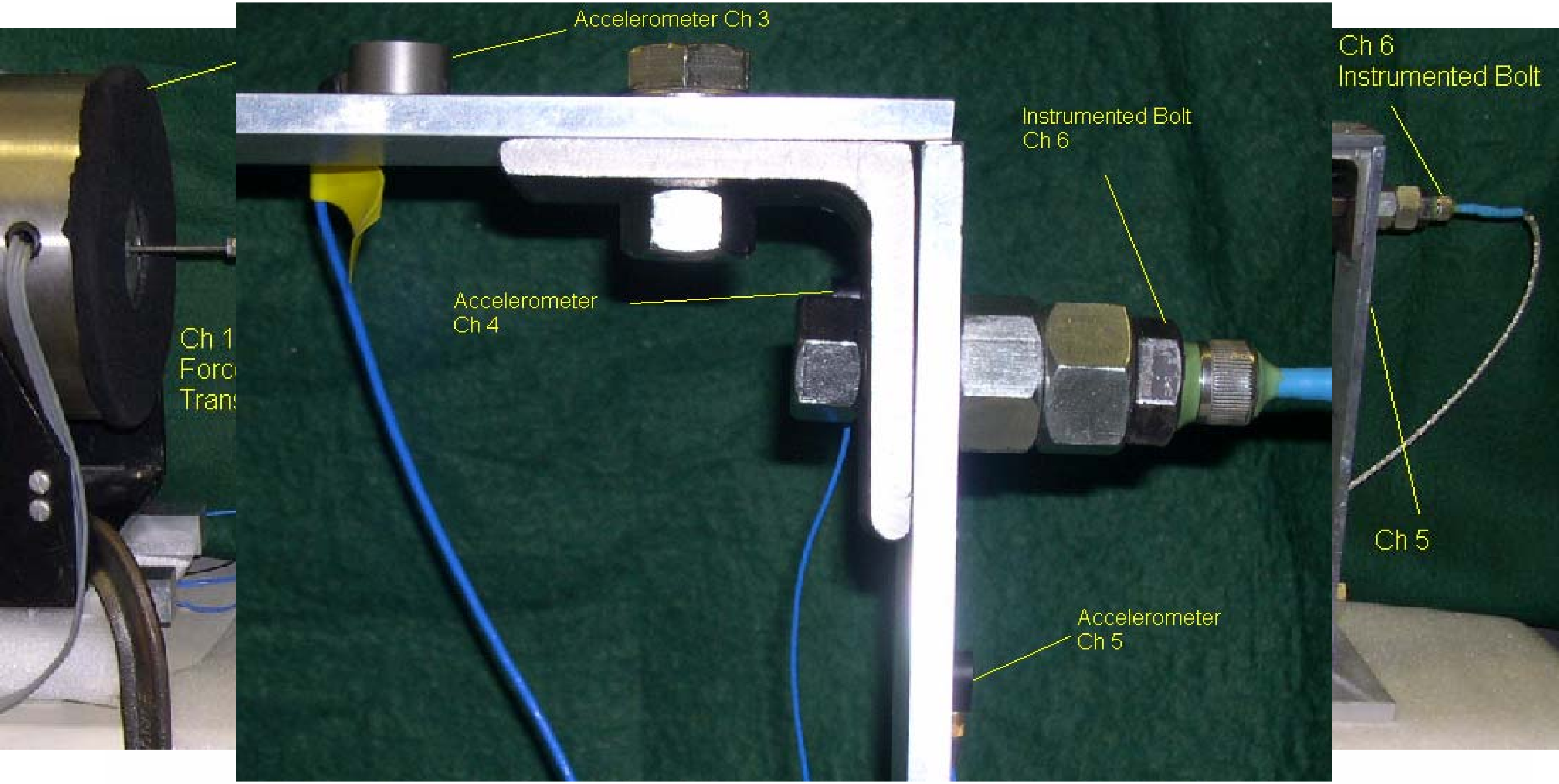
- Damage causes uncoupled responses
- Changes relationship between attractors



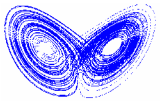
Cross-prediction error as a feature



Experimental Setup

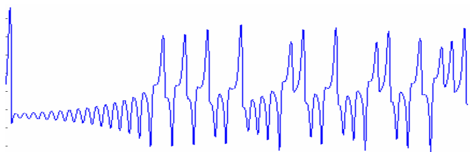


Experimental Procedure



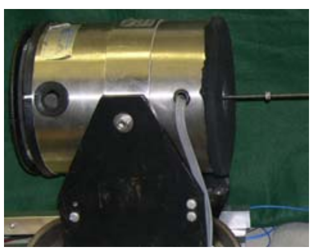
$$\dot{x} = q(y - x)$$
$$\dot{y} = -xz + rx - y$$
$$\dot{z} = xy - bz$$

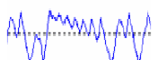
Numerically solve Lorenz differential equations

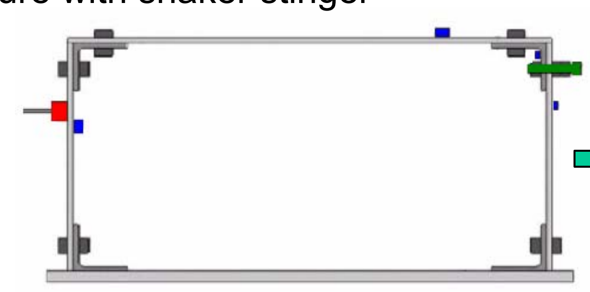


Select first coordinate as input voltage signal (deterministic)

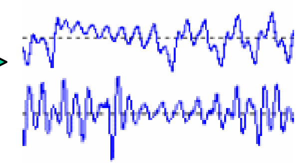
Excite structure with shaker stinger



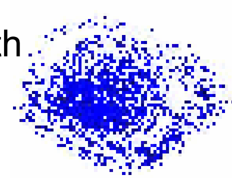




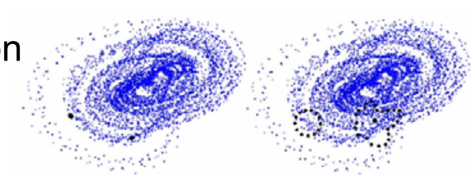
Measure accelerometer response signals at different locations



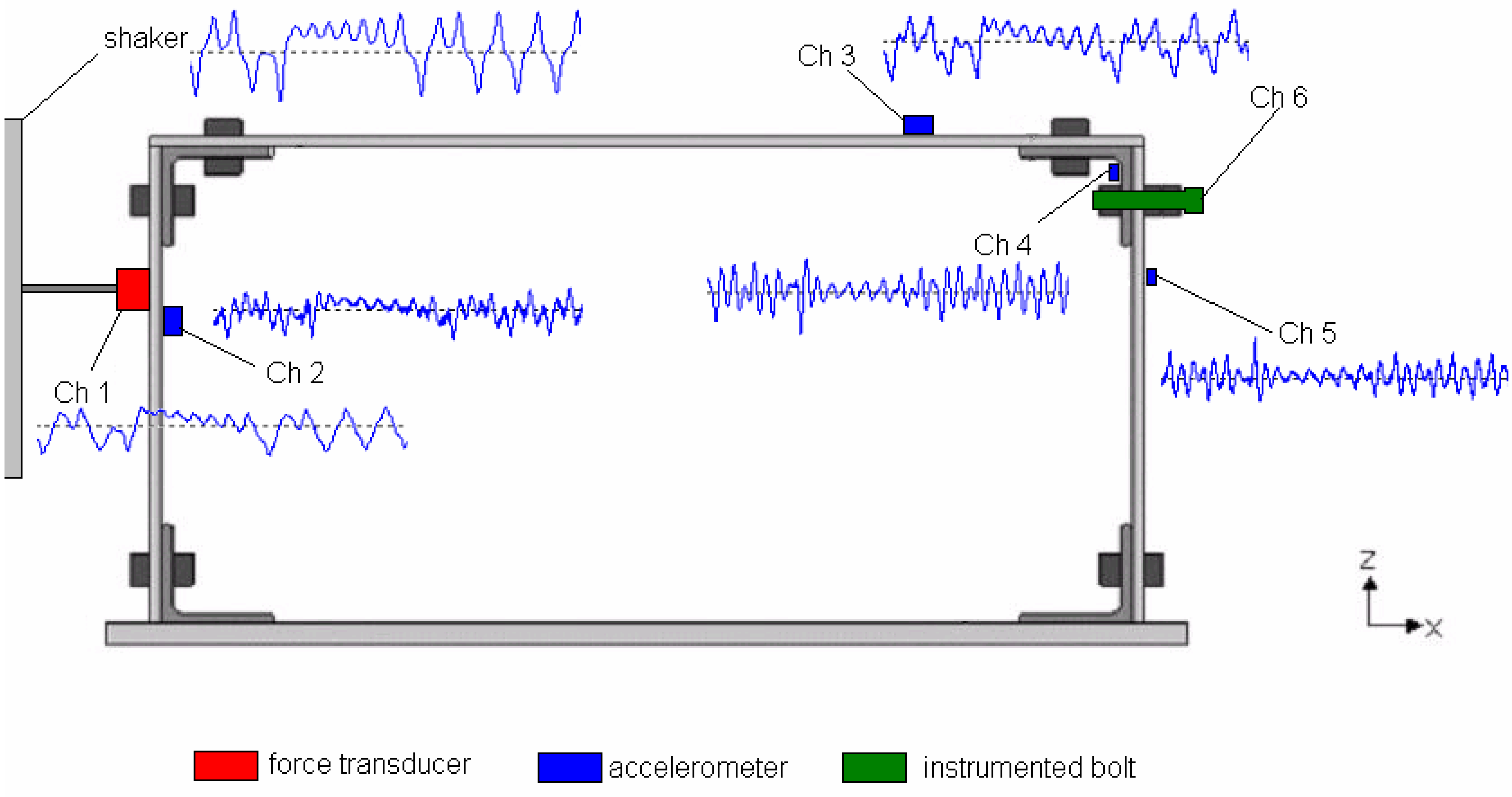
Reconstruct attractors with appropriate delay and embedding dimension



Calculate prediction errors between pairs of attractors

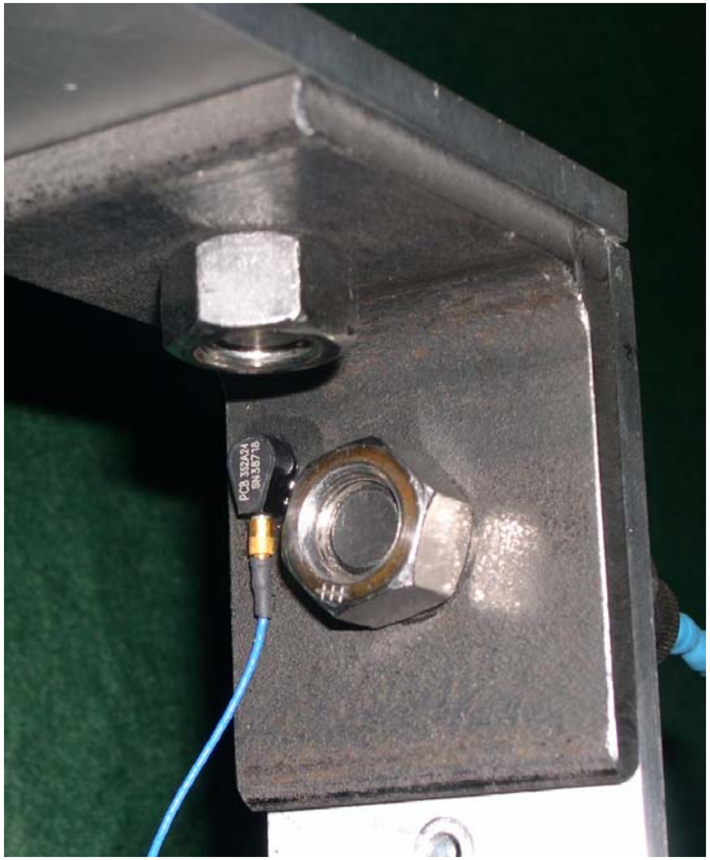


Typical input & output signals

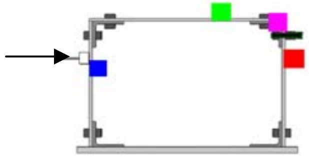


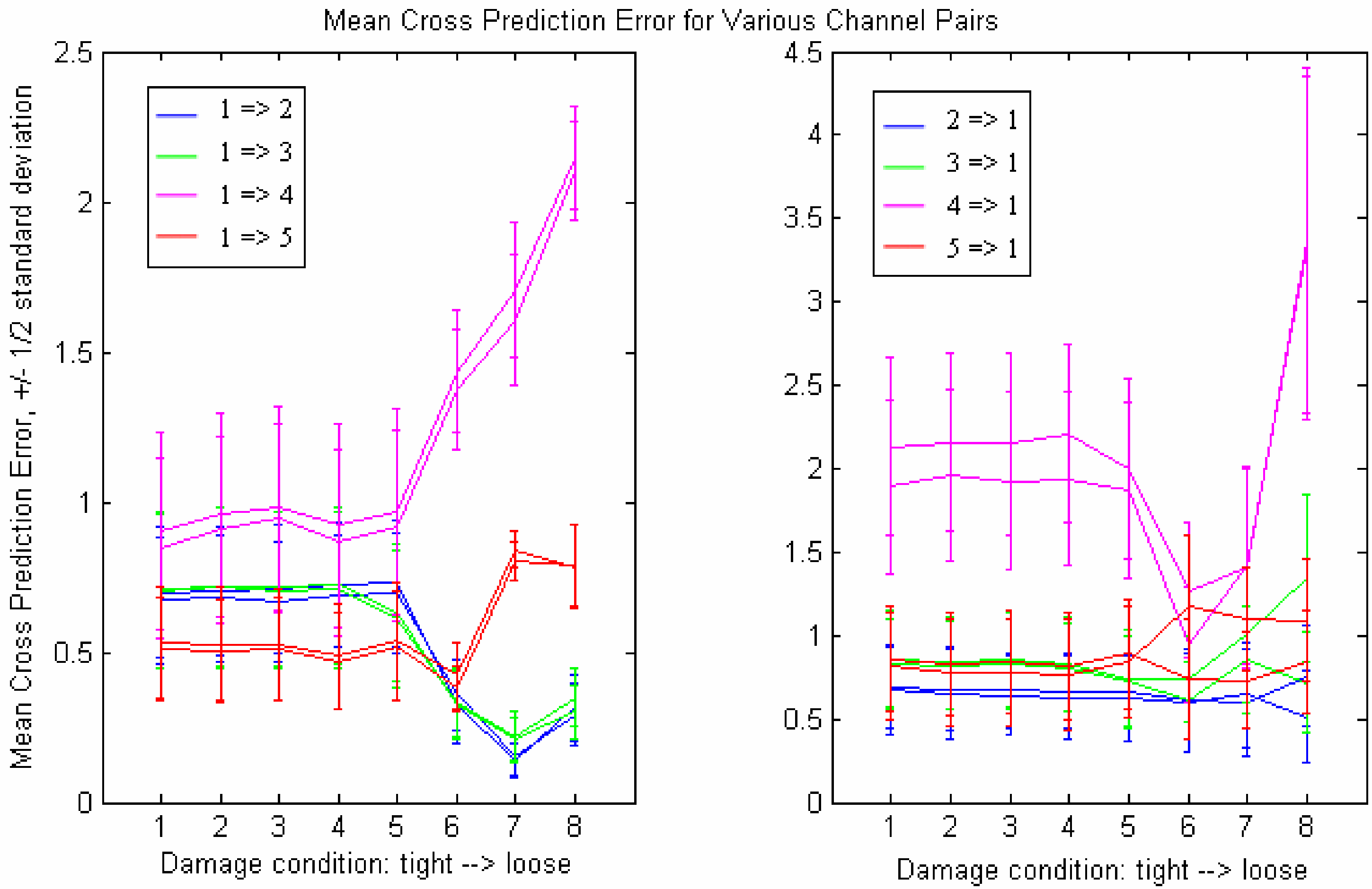
Damage Conditions

Damage Case	Description	Bolt Preload (N)
1	27 N-m torque	10400
2	14 N-m torque	7860
3	7 N-m torque	6420
4	3 N-m torque	5450
5	1 N-m torque	4780
6	Finger tight	4550
7	Loose no gap	--
8	Loose with gap	--

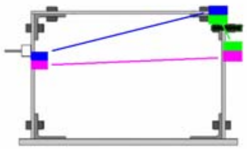


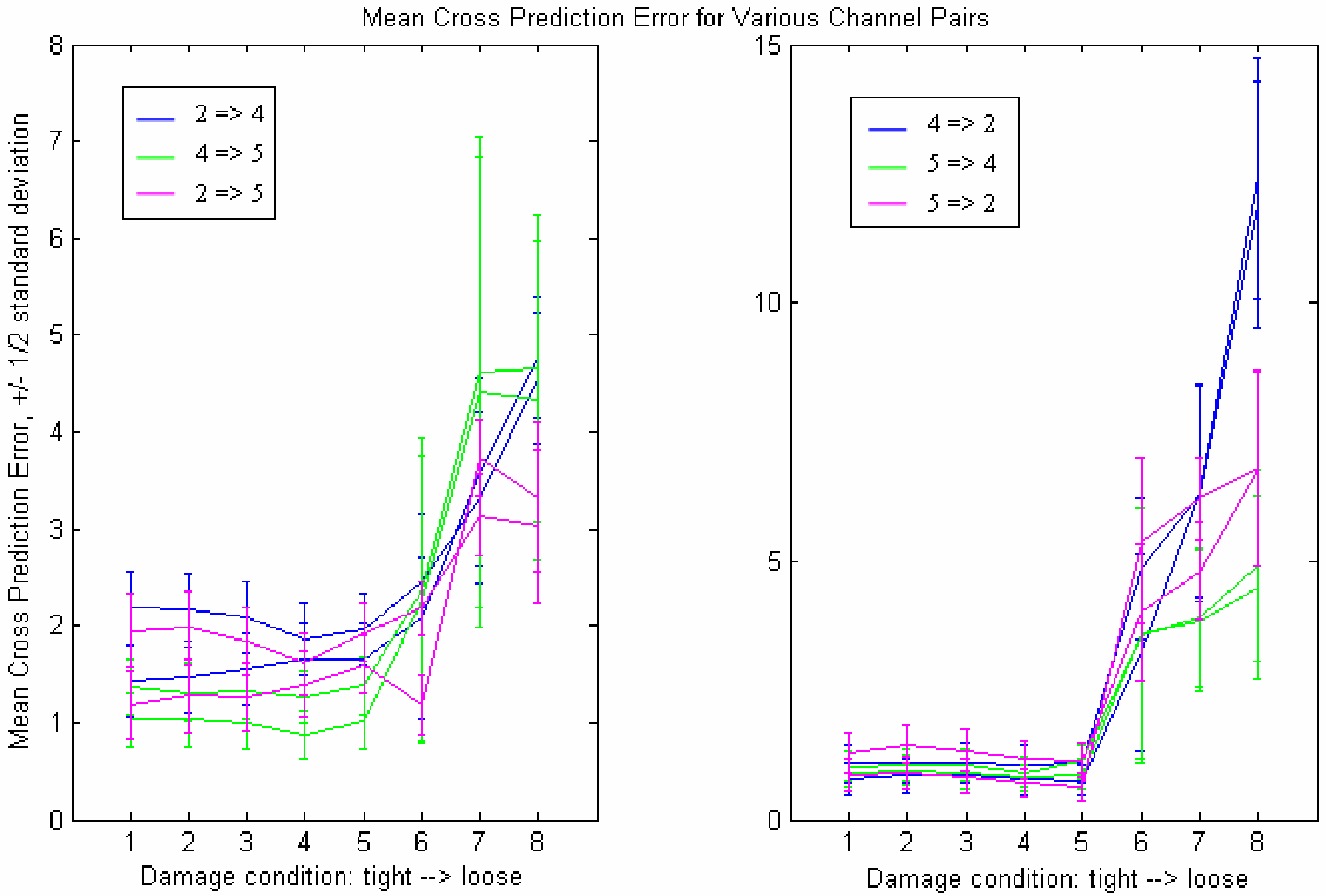
Excitation predicting response





Response pair predictions



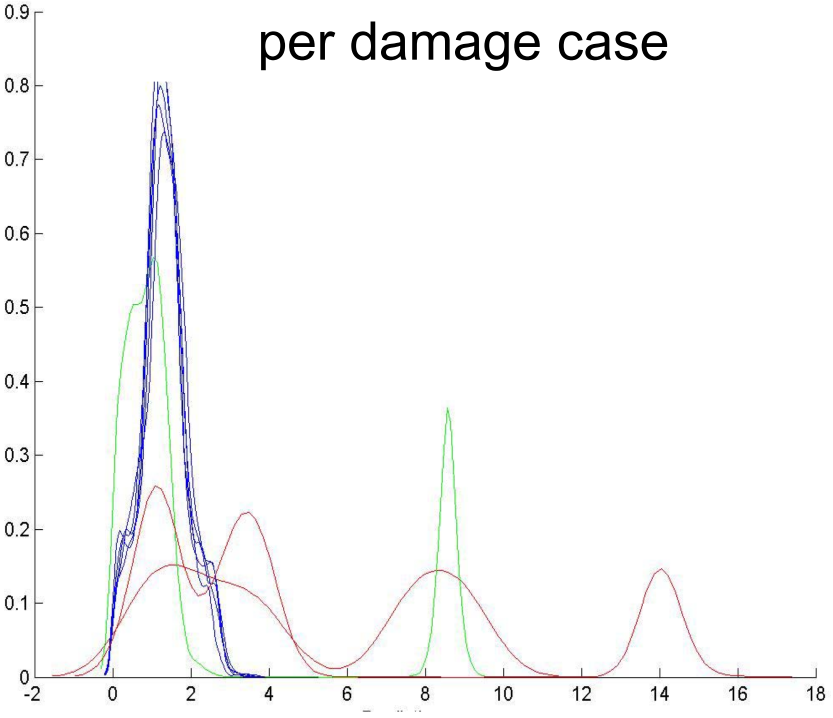


Statistical variation of results

- Large spread of prediction error with increasing damage

- One-sided Kolmogorov-Smirnov test distinguishes between the loose and tight damage conditions

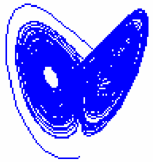
Prediction error distribution per damage case



Prediction error

Conclusions

- Able to detect loose bolt, but not extent of damage
- Able to qualitatively locate loose bolt by calculating error of excitation predicting response
- Both prediction error mean and standard deviation increase with damage, in selected cross-comparisons
- Need further detailed studies to quantify correlation between prediction error and bolt tension pre-load



Recommendations

- Use an instrumented bolt more sensitive to loads in the transition range
- Decrease computation time for practical applications
- Investigate sensitivity to:
  - Rate of input chaotic waveform
  - Relative direction of shaker excitation and loosened bolt
  - Accelerometer positions relative to damage
- Apply to other modes of failure

Acknowledgements

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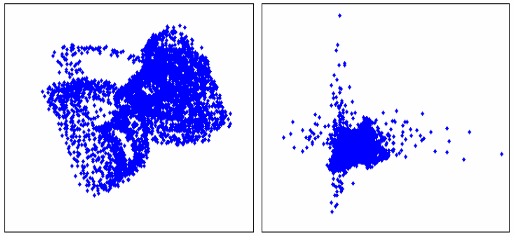
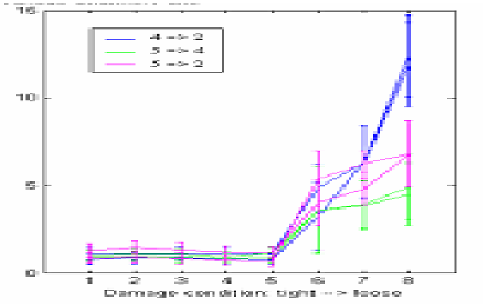
- Vibrant Technologies, for ME'ScopeVES
- Hibbitt, Karlsson, and Sorensen, Inc. for ABAQUS\CAE
- Dynamic Design Solutions, for FEMTools

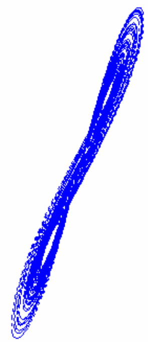
Questions or Comments?





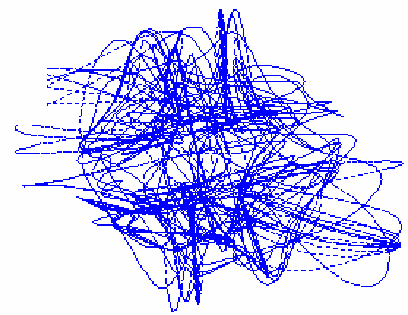
Choosing time delay T

- Maximize new information
  - Avoid redundancy
  - Still preserve relationship

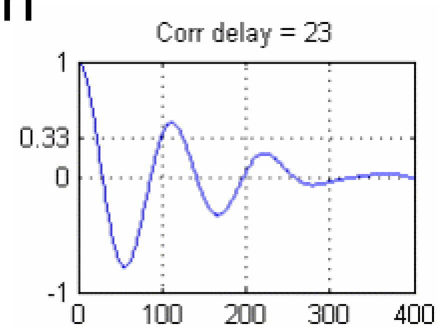


T too small:

over-correlated



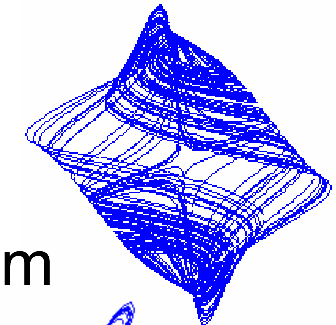
- Time when least self-correlated
  - Auto-correlation function
  - Mutual-information



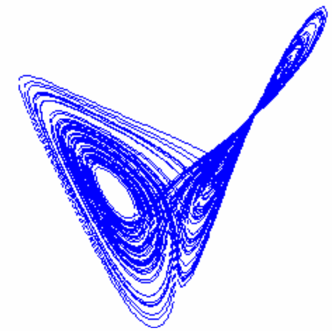
T too large:

unrelated

Choosing embedding dimension m



- Unambiguously ‘unfold’ attractor
  - Reveal system topography
  - Often lower dimension than original system



- False-nearest neighbors approach
  - Exclude temporal neighbors
  - Repeatedly embed until have few neighbors